Defence Applications of Agent-Based Information Fusion

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ABSTRACT

Information fusion and agent-based systems provide core capabilities in the NEC operational environment: uncertainty reduction and coordinated action. These are key enablers of situation assessment and effective resource allocation. In the military domain, uncertainty encompasses ambiguity and incompleteness, requiring flexible information fusion algorithms. Results and analysis are presented here for a Bayesian consensus algorithm applied to fault recovery in a sensor network, where some of the sensor fault types are unknown. The need for coordination raises architectural questions about where coordination is done and about its information exchange requirements. Two options are analysed: distributed coordination in which nodes establish shared situation awareness and run replicated central coordination algorithms, and decentralised agent-based coordination which is based on a market-based control representation. Decentralised coordination is shown to be more responsive than distributed coordination in sparsely connected networks with delays.

1.0 INTRODUCTION

The prime motivation for NATO's Network Enabled Capability (NEC) programme is information superiority. The challenge is to achieve this in an environment which is uncertain and dynamic, where resources are limited and continually vary during the course of operations. Information fusion is an established approach to the uncertainty problem. However, it is usual to consider uncertainty in its limited form as a statistical variation. This representation needs to be broadened for defence applications, where incompleteness and ambiguity are also prevalent. Information fusion algorithms generate situational and threat estimates, which provide a basis for coordinating resources to maximise effect. This raises a number of important architectural questions, such as: who is responsible for coordinating the resources, where within a networked system is this done, and what information is required? The multi-agent systems (MAS) approach represents this as a decentralised marked-based control problem. This involves repeated information exchange between sensor or platform agents until they converge (hopefully) on a desirable allocation of resources. Thus, the application of information fusion and MAS technology (or agent-based fusion for short) is appealing in the NEC defence context, but requires an analysis and understanding of (a) uncertainty in its broadest sense, and (b) the system implications of decentralised coordination.

This paper draws on work carried out by the author in collaboration with university partners under the UK ALADDIN project [1, 2]. Specifically, two problems of direct relevance to the information management-exploitation focus of these proceedings are considered. Section 2 considers the problem of networked sensor fusion in the presence of unreliable / untrustworthy sensor data. This work addresses incompleteness uncertainty as well as the more conventional random statistical uncertainty. Multi-sensor Bayesian consensus algorithms are used to demonstrate recovery from un-modelled sensor faults. Section 3 considers a core architectural question relating to distributed and decentralised coordination in the context of assigning a set of resources to a set of tasks. It is found that distributing shared awareness to every decision-maker in a network is outperformed (slower to respond), compared to a decentralised

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market-based control solution, when the network is subject to partial connectivity and delays. Section 4 provides a brief summary of the main results of these investigations and then draws some conclusions.

2.0 INFORMATION FUSION WITH UNRELIABLE DATA[1]

Information systems in NEC draw data from multiple sources (sensors, databases, etc) and share it over a communication network, typically after some local data reduction processes have been applied. A key challenge is to ensure statistically consistent estimates at every point in the network. In particular, the confidence attached to each estimate should never under-estimate the true confidence. This requirement is clearly under threat if there is an un-modelled source of unreliable data in the network, since its reported error (statistical variation) could badly misrepresent its true error (statistical variation + un-modelled component). Previous work has examined the problem of un-modelled correlation in sensor networks, which arises from 'double counting' of data due to communication loops and feedback in the network [3]. Here an alternative source of un-modelled data is considered: sensor faults and bias.

2.1 Problem Description

There are a number of reasons why sensors may generate intermittent faulty data. They include power failures, physical damage, and calibration error. In addition, human 'sensors' can mistype data entries into a tactical database, or adversaries could inject 'spoof' data into a network. Left unchecked, such data can rapidly propagate around a network and 'pollute' the situational and threat estimates at every node. This could have serious implications for decision-making and resource allocation.

Consider a sensor network comprising reliable sensors and unreliable sensors. Assume there are more reliable sensors than unreliable sensors and the unreliable sensors fail independently of one another. Each sensor node implements a local fault removal process to recover from a known set of fault types, but due to the presence of un-modelled faults there is some residual (unknown) error. The problem then is how to ensure consistent estimates at every node in the presence of unknown faults.

2.2 Algorithmic Approach

The ALADDIN project has developed a decentralised learning and data fusion algorithm to address the problem of recovery from unknown fault types. A detailed mathematical description of the algorithm is described in [4]; this section provides only a brief summary. The algorithm comprises two stages: (1) online learning of the sensor reliabilities and (2) consensus combination of the sensor data.

The online learning algorithm is implemented as a Bayesian recursion on each sensor node. This estimates the reliability of each sensor's data at the current time given all the data the sensor has generated up to that time. The recursion requires two inputs: a transition model for sensor reliability and a likelihood model for the sensor data. The transition model is straightforward: a sensor's reliability is assumed not to change unless there is evidence to suggest otherwise. The likelihood model is a monotonically decreasing function of the distance between a sensor's estimated report and its predicted report (e.g. Mahalanobis distance).

The consensus combination algorithm operates as follows. Consider two sensor reports and their associated probabilities of being reliable. There are four hypotheses: both sensors are reliable (in which case fuse them); sensor 1 reliable (keep) - sensor 2 unreliable (discard); sensor 1 unreliable (discard) - sensor 2 reliable (keep); both sensors are unreliable (discard). Mixture reduction is then used to combine the hypotheses and calculate a combined report. This process can be iterated over more than two sensors.

[1] Joint work with Steven Reece and Stephen Roberts (Oxford University) and Christopher Claxton (BAE Systems)

2.3 Examples and Results

As an illustrative example of the technique consider a sensor network comprising five sensors tasked with tracking a single target. Each sensor applies a local fault recovery algorithm matched to specific types of expected fault, e.g. drift, shock, and echo (see [4] for details). The outputs from this stage are displayed in the left column of Figure 1. One of the sensors (sensor 1) is reliable. Two of the sensors have a known fault type (sensor 4 – echo, sensor 5 – drift) and are therefore corrected by the local fault recovery algorithms. Two of the sensors have unknown fault type (sensors 2 and 3) created by injecting a constant bias term on top of a drift. The right column of Figure 1 display results from the online learning stage. As expected sensors 1, 4 and 5 are predicted to be reliable having gone through the local fault recovery processes, but sensors 2 and 3 are predicted to be unreliable after the onset time of the unknown faults.

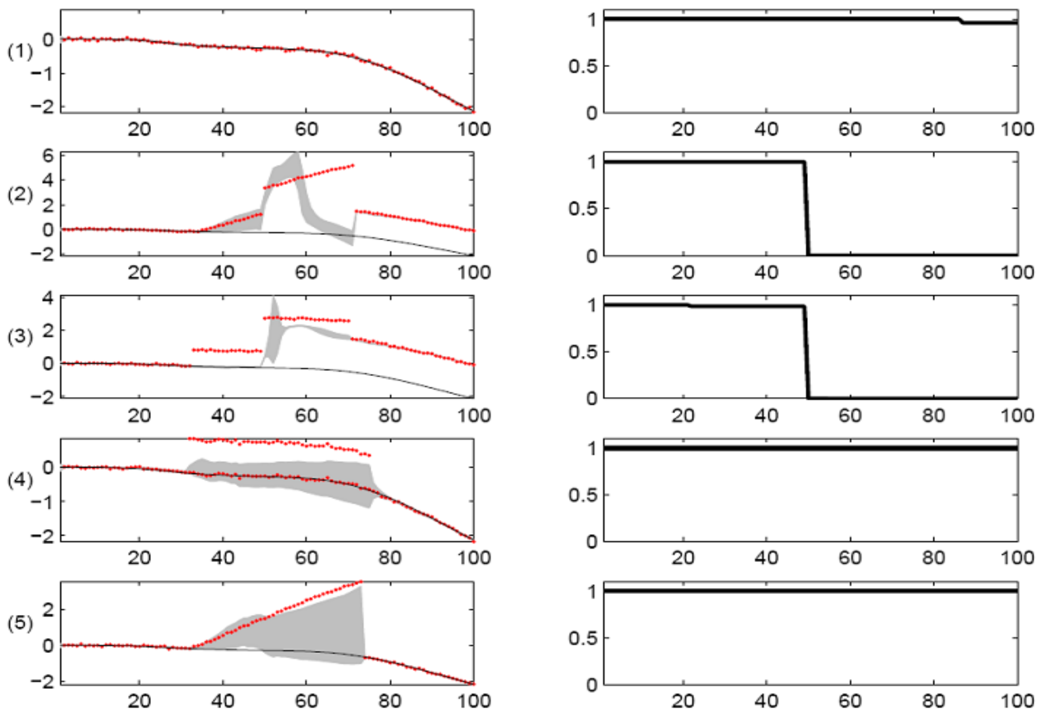

Figure 1: Shown on the left is the output at each sensor following its local fault recovery process. The red crosses are sensor measurements, the solid line is the true state, and the grey shading is the 1σ error about the estimated mean state. Shown on the right is the output from the online learning algorithm; sensors 3 and 4 are predicted to be unreliable.

The outputs from the local fault recovery processes and the online learning algorithms are then input to the consensus algorithms running on each node. They attempt to recover from any residual unknown faults that may be present in the system. The output at one node for the example problem is displayed in Figure 2. This demonstrates that the underlying state is being tracked despite the presence of the unknown faults.

3.0 DECENTRALISED AGENT-BASED COORDINATION

Coordinated action is imperative in a multi-actor NEC information system. Suppose there are two resources and two tasks. Without coordination the resources move to their nearest task potentially leaving a task unattended; with coordination such conflicts are removed and both tasks are attended. Given that coordination is required to maximise the effect of limited resources, this section considers where coordination should be done within a networked system. Specifically, we consider two architectural

options aligned with the information-sharing NEC concept: distributed coordination and decentralised agent-based coordination.

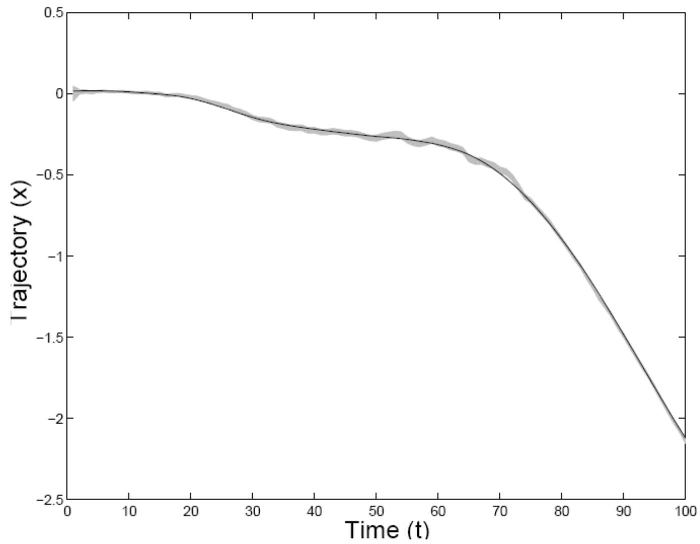

Figure 2: Result of applying the consensus algorithm to outputs from the initial fault recovery processes at five sensor nodes. The estimated state follows the true state despite the presence of unknown faults in two of the sensors.

Distributed coordination is achieved by replicating a central coordinator at each node in the NEC system. The nodes must first establish shared situation awareness via communication and/or use of prior knowledge about the state of the environment. Then each node runs a central resource allocation algorithm to generate system-wide actions and carries out its designated action. The collective actions are guaranteed to be coordinated (assuming perfect shared awareness) due to the global nature of the central algorithms.

Decentralised agent-based coordination treats resource allocation as a market-based control problem. The resources (agents) bid for tasks according to the net gain in information they expect to acquire as a result of being allocated to those tasks. The agents communicate bids with their neighbours over a communication network until the negotiations settle on an equilibrium set of actions, which they then execute. This can run asynchronously and there is no need to wait to establish shared situation awareness.

3.1 Problem Description

The simple one-to-one resource allocation problem is considered as a focus for this study. That is, given a set of resources and tasks, each resource can be allocated to at most one task. Consider N resources and an equal number of stationary tasks positioned randomly within a 2-D square world of side length W. Each resource is equipped with a combat-net radio broadcast device and communicates according to a time-division-multiple-access (TDMA) protocol. This means that each node has a designated communication time-slot; a round-robin sequential communication order is imposed on the nodes. Suppose that communication bandwidth is restricted to the extent that each node can only broadcast a vector of size $N_{\min}$ in its designated time slot and each broadcast incurs a communication delay T.

Distributed and decentralised coordination are expected to incur different total amounts of communication delay (computation delays are assumed to be negligible here). For distributed coordination the delays are due to the communications required to establish shared situation awareness at each node. For decentralised coordination the delays are due to the communications required to negotiate on tasks until equilibrium is

reached. Delays impact on the response time of the system which in turn impacts the operational benefit resulting from a resource allocation, since benefits typically degrade in proportion to the total allocation delay time. The problem is to quantify this and analyse how performance depends on communication network topology and delay time.

3.2 Algorithmic Approach

The distributed coordination system runs an identical central resource allocation algorithm on each node. For the one-to-one resource allocation problem the polynomial-time Munkres (or Hungarian) algorithm [5] is deployed. This requires nodes to broadcast their individual utility (or cost) vectors for their task list until a full utility matrix is available at each node. Then the Munkres algorithm can be ran at each node to calculate the total utility-maximising allocation of resources to tasks.

The particular decentralised coordination algorithm used for this study is a two phase algorithm comprising: (1) an auction phase, and (2) a consensus phase. These phases are run iteratively on each node until the algorithm converges (see [6] for algorithmic details and convergence proofs). The algorithm requires nodes to broadcast their most current 'price' list for the tasks. This information propagates or 'diffuses' around the network as a result of nodes updating their price lists during the consensus phase. Note this is not the case for the distributed coordination solution since information utility vectors have to be explicitly relayed between non-neighbouring nodes.

3.3 Examples and Results

The first example focuses on a fully connected communication network with zero delays. The distributed solution is optimal in this case and the sub-optimality of the decentralised agent-based solution and its dependence on the size of the system is of interest. In this example the static benefit awarded for assigning a resource i to a task j was drawn from a uniform distribution. This discounted by a factor $\lambda^{\tau_{ij}}$ where λ is fixed at a value 0.97 and τ_{ij} is the time taken for the resource to travel to the task (the resources have identical constant speeds). The problem was simulated for a number of different random realisations of the resource and task positions, enabling mean performance levels to be calculated.

The result of this example is displayed in Figure 3, which plots the ratio of the total allocation benefit for the decentralised solution relative to the distributed solution for a varying number of resources (where number of resources = number of tasks) . It is found that the resource allocation benefits for the decentralised solution are only about 3% less than they are for the distributed solution. This value is roughly constant for between 5 to 40 resources.

The next example investigates the effect of reducing the density of the communicating network and introducing delays. The density of the network is influenced by varying the communication range of the TDMA broadcast system. Specifically, results are obtained for a normalised communication range of between 1 and 0.1 (where 1 equates to the diagonal distance from the centre of the square world to a corner) and communication delays of 10, 50, 100 and 200ms. Figure 4 displays the number of communication broadcasts required to generate a resource allocation solution for the distributed and decentralised approaches. This is proportional to their response times since each broadcast incurs a delay.

When the normalised communication range is > 0.6 the network is reasonably dense and the distributed solution is more responsive than the decentralised solution. However, as communication range decreases it reduces the connectivity of the network and the performance of the decentralised solution is much better.

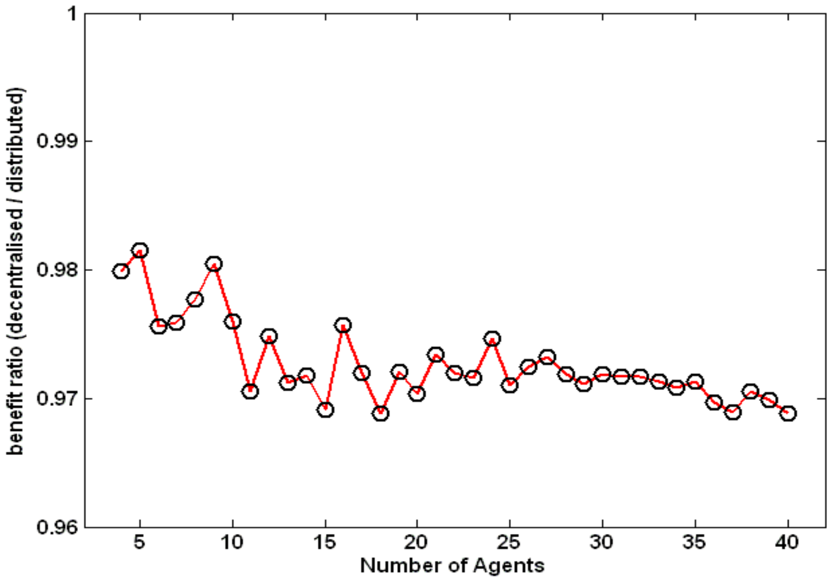

Figure 3: Benefit of decentralised solution relative to distributed solution for varying number of resources / agents in the case of a fully-connected communication network with zero delays.

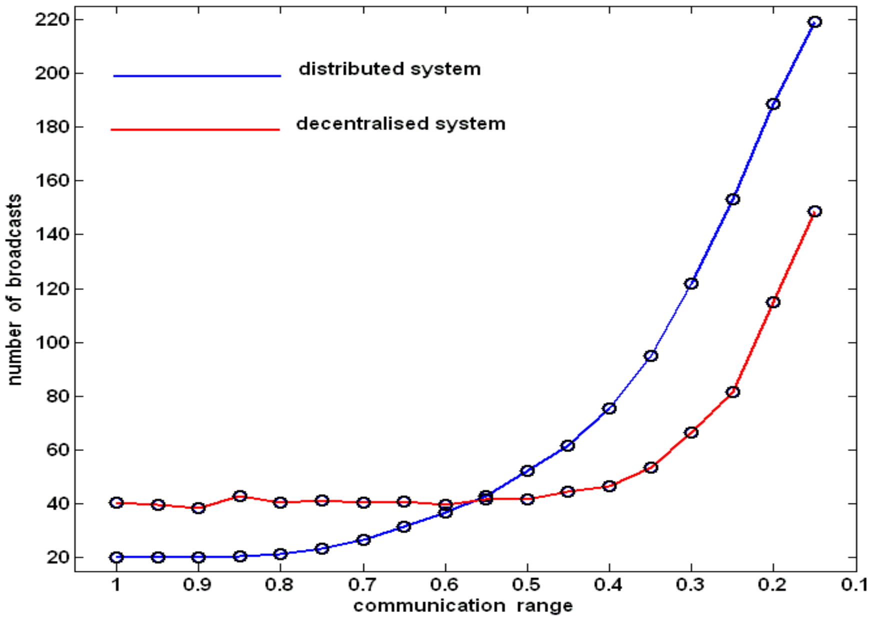

Figure 4: For varying communication range, the curves show the number of communication broadcasts required until a resource-task allocation solution can be generated.

The delays incurred by broadcasting utility vectors (in the distributed solution) or price vectors (in the decentralised solution) further discount the benefits obtained by allocating the resources. Figure 5 displays the discounted benefit of the decentralised solution relative to the distributed solution for four different communication delay times. The previous results have already shown that the decentralised solution is more responsive for sparse networks. Figure 5 translates this result into benefits and shows how communication delays can have a significant impact on performance.

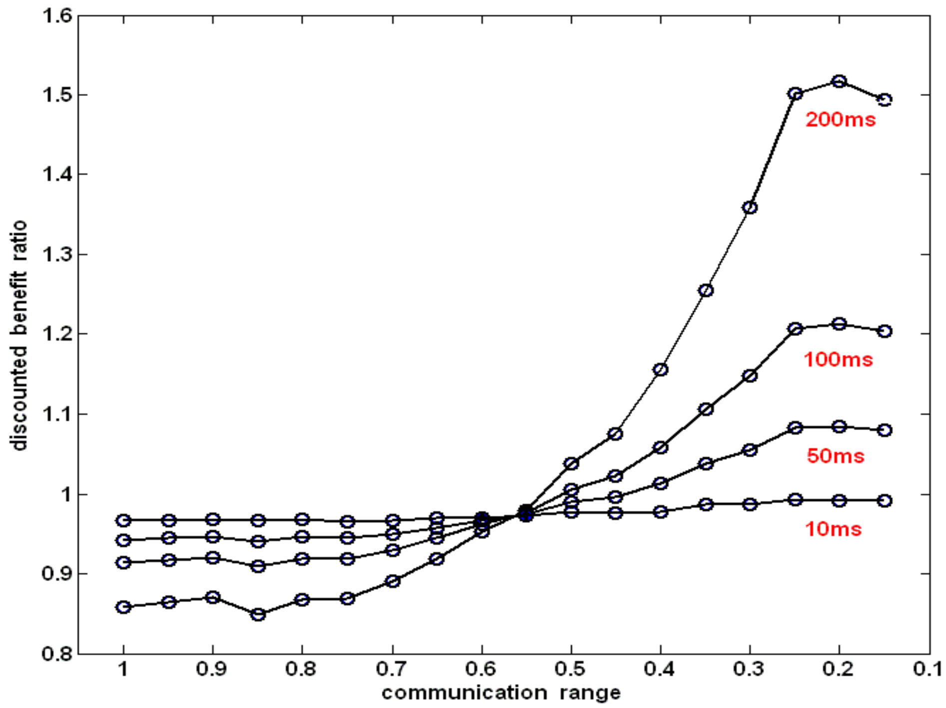

Figure 5: For varying communication range, the curves show the discounted benefit of the decentralised solution relative to the distributed solution for different communication delays.

4.0 DISCUSSION AND CONCLUSIONS

This paper has considered information fusion and multi-agent system technologies in the context of NEC. These technologies address two key concerns in the military operational environment: uncertainty reduction and resource coordination. Arguably, these technologies should be integrated into a single overarching framework, agent-based information fusion, because information metrics provide a rigorous basis for decision-making under uncertainty. The development and application of such a framework has been the main research driver of the UK's ALADDIN project (and its precursor project ARGUS II [7]).

The defence domain is particularly complex and this paper considered two aspects of that complexity. First, uncertainty is present in a variety of forms including the more typical "known unknowns" but also the "unknown unknowns." Faulty data in sensor networks was presented as an example of this. A Bayesian consensus algorithm enabled fault recovery in the presence of faults of unknown type providing the number of reliable sensors in the network outweighed the number of unreliable sensors. Second, coordination of resources relies on communication to remove conflicting local decisions about task allocation. Distributed and decentralised agent-based coordination mechanisms were considered for a simple one-to-one task allocation problem. The decentralised solution was more responsive under the conditions of sparse network connectivity and large communication delays typical of military operations.

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